Ask The Application Engineer—36

Wideband A/D Converter Front-End Design Considerations II:

Amplifier- or Transformer Drive for the ADC?

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Design of the input configuration, or "front end," ahead of a high-performance analog-to-digital converter (ADC) is critical to achieving desired system performance. Optimizing the overall design depends on many factors, including the nature of the application, system partition, and ADC architecture. The following questions and answers highlight the important practical considerations affecting the design of an ADC front end using amplifier- and transformer circuitry.

Q. *What is the fundamental difference between amplifiers and transformers?*

A. An amplifier is an active element, while a transformer is passive. Amplifiers, like all active elements, consume power and add noise; transformers consume no power and add negligible noise. Both have dynamic effects to be dealt with.

Q. *Why would you use an amplifier?*

A. Amplifier performance has fewer limitations than those of transformers. If dc levels must be preserved, an amplifier must be used, because transformers are inherently ac-coupled devices. On the other hand, transformers provide galvanic isolation if needed. Amplifiers provide gain more easily because their output impedance is essentially independent of gain. On the other hand, a transformer's output impedance increases with the square of the voltage gain—which depends on the turns ratio. Amplifiers provide flatter response in the pass band, free of the ripple due to the parasitic interactions in transformers.

Q. *How much noise does an amplifier typically add, and what can I do to reduce this?*

A. A typical amplifier that might be considered, the ADA4937,[1] for example, when configured for G = 1, has an output noise spectral density of 6 nV/√Hz at high frequencies, compared to the 10-nV/√Hz input noise spectral density of the 80-MSPS AD9446-80[2] ADC. The problem here is that the amplifier has a noise bandwidth equivalent to the full bandwidth of the ADC, around 500 MHz, while the ADC noise is folded to one Nyquist zone (40 MHz). Without a filter, the integrated noise then becomes 155 μV rms for the amplifier and 90 μV rms for the ADC. Theoretically, this degrades the overall system SNR (signal-to-noise ratio) by 6 dB. To confirm this experimentally, the measured SNR, with the ADA4937 driving the AD9446-80, is 76 dBFS, and the noise floor is –118 dB (Figure 1). With a transformer drive, the SNR is 82 dBFS. The driver amplifier has thus degraded the SNR by 6 dB.

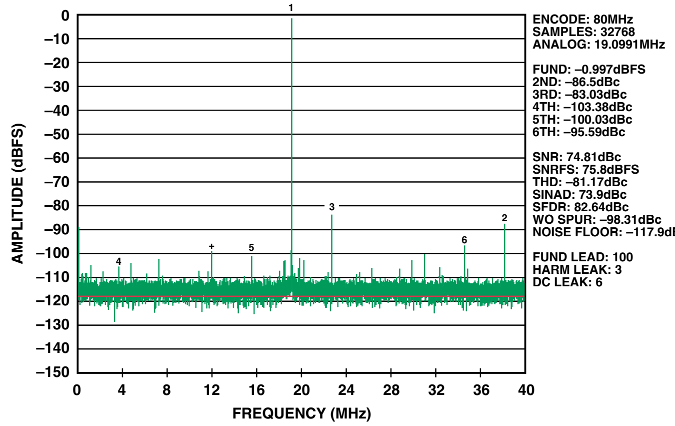

Figure 1. ADA4937 amplifier driving an AD9446-80 ADC at 80 MSPS without a noise filter.

To make better use of the ADC's SNR, a filter is inserted between the amplifier and ADC. With a 100-MHz 2-pole filter, the amplifier's integrated noise becomes 71 μV rms, degrading the ADC's SNR by only 3 dB. Use of the 2-pole filter improves the SNR performance of the Figure 1 circuit to 79 dBFS, with a noise floor of –121 dB, as shown in Figure 2a. The 2-pole filter is built with 24-Ω resistors and 30-nH inductors in series with each of the amplifier's outputs, and a 47-pF differentially connected capacitor (Figure 2b).

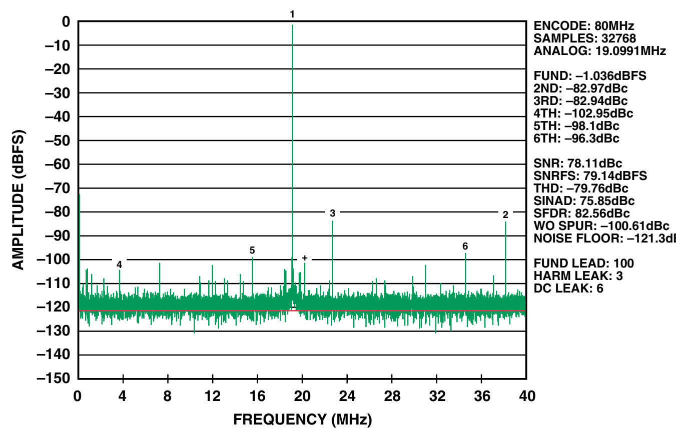

Figure 2a. Driving an AD9446-80 with a 100-MHz noise filter.

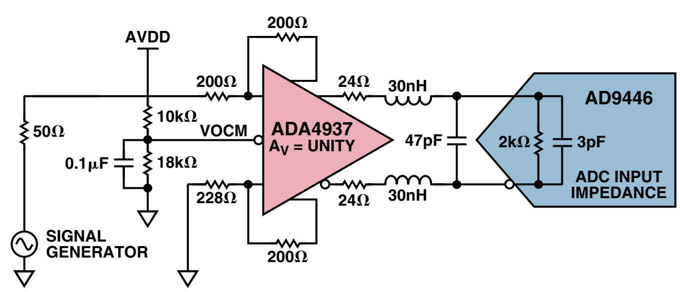

Figure 2b. Schematic diagram of ADA4937 amplifier driving an AD9446-80 ADC at 80 MSPS with a 2-pole noise filter.

Q. *How do high-speed amplifiers and ADCs compare in power consumption?*

A. This depends on the amplifier and ADC used. Two typical amplifiers, with similar power consumption, are the AD8352,[3] which draws 37 mA @ 5 V (185 mW), and the ADA4937, which draws 40 mA @ 5 V (200 mW). Overall power consumption can be reduced by about one-third, with slightly degraded performance, by using a 3.3-V supply. ADCs feature more diversity in power consumption, depending on resolution and speed. The 16-bit, 80-MSPS AD9446-80 draws 2.4 W, the 14-bit, 125-MSPS AD9246-125[4] draws 415 mW, and the 12-bit, 20-MSPS AD9235-20[5] draws only 95 mW.

Q. *When do you need to use a transformer?*

A. Transformers offer the biggest performance advantage compared to amplifiers at very high signal frequencies and when significant additional noise cannot be tolerated at the ADC input.

Q. *How do transformers and amplifiers differ when providing gain?*

A. The main difference is in the impedance they present to the ADC input, which directly affects system bandwidth. A transformer's input- and output impedance are related by the square of the turns ratio, while an amplifier's input and output impedance are essentially independent of gain.

For example, when a $G = 2$ transformer is used from a 50-Ω source impedance, the impedance seen at the secondary side of the transformer is 200 Ω. The AD9246 ADC has a differential input capacitance of 4 pF which, coupled with the 200-Ω transformer impedance, reduces the ADC's –3-dB bandwidth from 650 MHz to 200 MHz. Extra series resistance and differential capacitance are often needed to improve performance and reduce kickback from the converter, which can limit –3-dB bandwidth further, possibly to 100 MHz.

When a low-output-impedance amplifier—such as the ADA4937—is used, the result is a very low source impedance, usually less than 5 Ω. 25-Ω transient-limiting resistors can be used in series with each ADC input; in the case of the AD9246, the ADC's full 650-MHz analog input bandwidth would be usable.

So far the discussion has been about –3-dB bandwidths. When tighter flatness is needed, say 0.5 dB in a 1-pole system, the −3-dB bandwidth needs to be about 3× wider. For 0.1-dB flatness with one pole, the ratio increases to 6.5×. If 0.5-dB flatness is required at up to 150 MHz, a –3-dB bandwidth greater than 450 MHz is required, which is difficult to attain with a $G = 2$ transformer but is straightforward with a low-output-impedance amplifier.

Q. *What are the factors to consider in choosing a transformer or an amplifier to drive an ADC?*

A. They can be boiled down to a half-dozen parameters—outlined in this table:

Parameter	Usual preference
Bandwidth	Transformer
Gain	Amplifier
Pass band flatness	Amplifier
Power requirement	Transformer
Noise	Transformer
DC vs. ac coupling	Amplifier (dc level preservation) Transformer (dc isolation)

Applications in which key parameters are in conflict require additional analysis and trade-offs.

Q. *What are some considerations in this analysis?*

A. One must start by understanding the level of difficulty in designing a front end for a given ADC. First, is the ADC internally buffered, or is it unbuffered (for example, a switched-capacitor type)? Naturally, the level of difficulty increases as the frequency increases in either case. But switched-capacitor types are more difficult for the designer to deal with.

If gain is needed to make full use of the ADC's input range, an application that might otherwise favor a transformer becomes more difficult as the required gain (turns ratio) increases.

Of course, the difficulty increases with frequency. Design of an IF system below 100 MHz with a buffered ADC would be relatively simple compared to a high-IF design with low signal levels using an unbuffered ADC, as Figure 3 illustrates. With so many parameters pulling in different directions, trade-offs are sometimes difficult and often puzzling to keep track of as components are changed and evaluated.

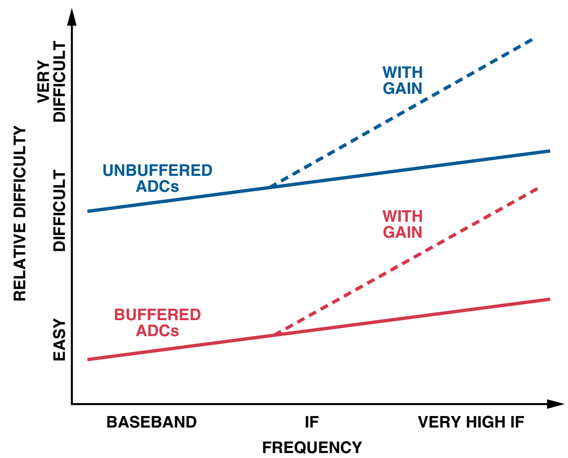

Figure 3. Frequency vs. relative difficulty.

It may be useful to employ a spreadsheet or table to keep all of the parameters straight as the design moves forward. There is no optimum design to satisfy all cases; it will be subject to the available components and the application specifications.

Q. *OK, design can be difficult. Now how about some details regarding system parameters ?*

A. First, it is paramount that everything be taken into account when designing an ADC front end! Each component should be viewed as part of the load on the previous stage; and maximum power transfer occurs when Z_{SOURCE} = conjugate Z_{LOAD} (Figure 4).

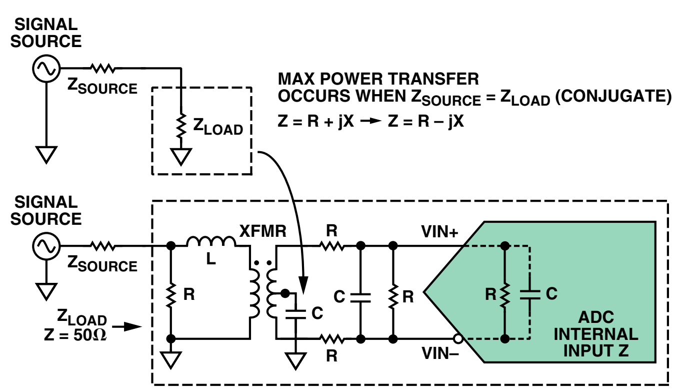

Figure 4. Maximum power transfer.

Now to the design parameters:

Input impedance is the characteristic impedance of the design. In most cases it is 50 Ω, but different values may be called for. The transformer makes a good transimpedance device. It allows the user to couple between different characteristic impedances when needed and fully balance the overall load of the system. In an amplifier circuit, the impedance is specified as an input- and output characteristic that can be designed to not change over frequency as a transformer might.

Voltage standing-wave ratio (VSWR) is a dimensionless parameter that can be used to understand how much power is being reflected into the load over the bandwidth of interest. An important measure, it determines the input drive level required to achieve the ADC's full-scale input.

Bandwidths are ranges of frequencies used in the system. They can be narrow or wide, at baseband, or covering multiple Nyquist zones. Their frequency limits are typically the –3-dB points.

Pass-band flatness (also *gain flatness*) specifies the amount of (positive and negative) variation of response with frequency within a specified bandwidth. It may be a ripple or simply a monotonic rolloff, like a Butterworth filter characteristic. Whatever the case, pass-band flatness is usually required to be *less than or equal to* 1 dB and is critical for setting the overall system gain.

Input drive level is determined by the system gain needed for the particular application. It is closely related to the bandwidth specification and depends on the front-end components chosen, such as the filter and amplifier/transformer; their characteristics can cause the drive level requirement to be one of the most difficult parameters to maintain.

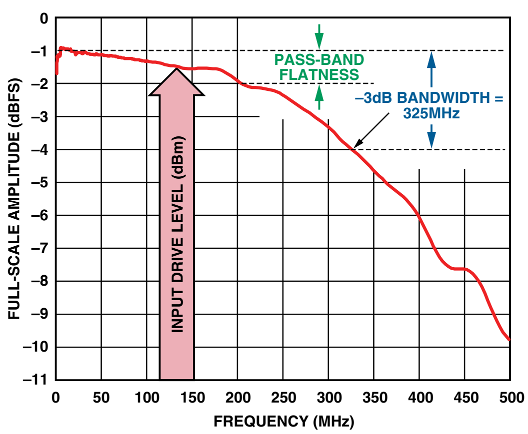

Figure 5. Bandwidth, pass-band flatness, and input drive level defined.

Signal-to-noise ratio (SNR) is the log-ratio of the rms value of the full-scale signal to the root-sum-square of all noise components within a given bandwidth, but not including distortion components. In terms of the front end, SNR degrades with increased bandwidth, jitter, and gain (at high gains, amplifier noise components that may have been negligible at low gain can become significant).

Spurious-free dynamic range (SFDR) is the ratio of the rms full-scale value to the rms value of the largest spurious spectral component. Two major contributors of spurs at the front end are the nonlinearity of the amplifier (or the transformer's lack of perfect balance), which produces mostly second-harmonic distortion—and the input mismatch and its amplification by the gain (at higher gain, matching is more difficult and parasitic nonlinearities are amplified), generally seen as a third-harmonic distortion.

Q. *What is important to know about transformers?*

A. Transformers have many different characteristics—such as voltage gain and impedance ratio, bandwidth and insertion loss, magnitude- and phase imbalance, and return loss. Other requirements may include power rating, type of configuration (such as balun or transformer), and center-tap options.

Designing with transformers is not always straightforward. For example, transformer characteristics change over frequency, thus complicating the model. An example of a starting point for modeling a transformer for ADC applications can be seen in Figure 6. Each of the parameters will depend on the transformer chosen. It is suggested that you contact the transformer manufacturer to obtain a model if available.

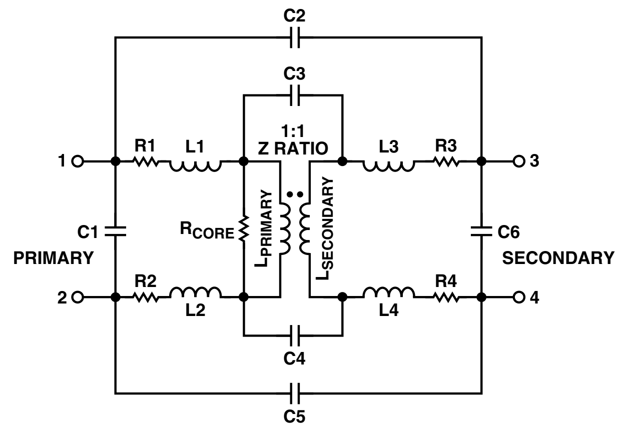

Figure 6. Transformer model.

Among the characteristics of a transformer:

Turns ratio is the ratio of the secondary- to the primary voltage.

Current ratio is inversely related to the turns ratio.

Impedance ratio is the square of the turns ratio.

Signal gain is ideally equal to the turns ratio. Although voltage gains are inherently noise-free, there are other considerations—to be discussed below.

A transformer can be viewed simplistically as a pass-band filter with nominal gain. **Insertion loss,** the filter's loss over the specified frequency range, is the most common measurement specification found in a data sheet, but there are additional considerations.

Return loss is a measure of the mismatch of the effective impedance of the secondary's termination as seen by the primary of a transformer. For example, if the square of the ratio of secondary to primary turns is 2:1, one would expect a 50-Ω impedance to be reflected onto the primary when the secondary is terminated with 100 Ω. However, this relationship is not exact; for example, the reflected impedance on the primary changes with frequency. In general, as the impedance ratio goes up, so does the variability of the return loss.

Amplitude- and **phase imbalance** are critical performance characteristics when considering a transformer. These two specifications give the designer a perspective on how much nonlinearity to expect when a design calls for very high (above 100-MHz) IF frequencies. As the frequency increases, the nonlinearities of the transformer also increase, usually dominated by phase imbalance, which translates to even-order distortions (mainly 2^{nd}-harmonic).

Figure 7 shows typical phase imbalance as a function of frequency for single- and double-transformer configurations.

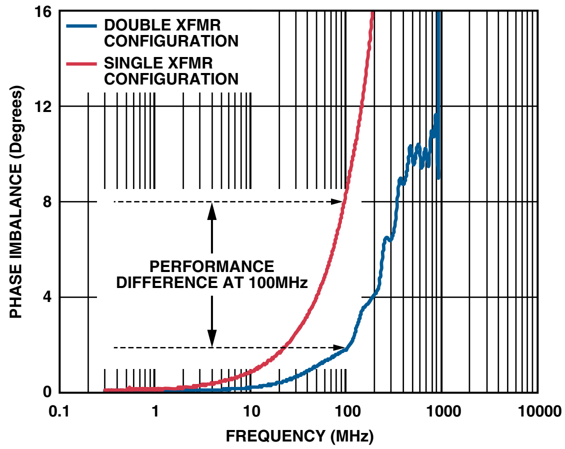

Figure 7. Transformer phase imbalance for single- and double-transformer configurations.

Remember, not all transformers are specified the same way by all manufacturers, and transformers with apparently similar specs may perform differently in the same situation. The best way to select a transformer for your design is to collect and understand the specs of all transformers being considered, and request any key data items not stated on manufacturers' data sheets. Alternatively, or in addition, it may be useful to measure their performance yourself using a network analyzer.

Q. *Which parameters are important in choosing an amplifier?*

A. The principal reason for using an amplifier instead of a transformer is to get better *pass-band flatness*. If this specification is critical to your design, an amplifier should produce less variability, typically ±0.1 dB over the frequency range. Transformers have lumpy response and require "fine tuning" when they must be used and flatness is an issue.

Drive capability is another advantage of amplifiers. Transformers are not made for driving long traces on PC boards. They are intended for direct connection to the ADC. If the system requirements dictate that the "driver/coupler" needs to be located far away from the ADC, or on a different board, an amplifier is strongly recommended.

DC coupling can also be a reason for using an amplifier, since transformers are inherently ac-coupled. Some high-frequency amplifiers can couple at frequencies all the way down to dc, if that part of the spectrum is important in the application. Typical amplifiers to consider include the AD8138 and ADA4937.

Amplifiers can also provide dynamic isolation, roughly 30 dB to 40 dB of reverse isolation, to squelch kickback glitches from current transients in an unbuffered ADC's input.

If the design calls for wideband gain, an amplifier provides a better match than a transformer to the ADC's analog inputs.

Another trade-off is bandwidth vs. noise. For designs involving frequencies greater than 150 MHz, transformers will do a better job of maintaining SNR and SFDR. However, within the first or second Nyquist zone, either a transformer or an amplifier can be used.

Q. *What are the preferred ADI amplifiers for driving high-performance ADCs?*

A. A handful of amplifiers are best for high-speed ADC front ends. These include the AD8138[6] and AD8139;[7] the AD8350,[8] AD8351,[9] and AD8352;[10] and the ADA4937 and ADA4938.

The AD8139 is commonly used for *baseband* designs, i.e., where input frequencies of interest are less than 50 MHz. For higher-IF designs the AD8352 is commonly used. This amplifier shows good noise- and spur rejection over a much wider band of frequencies, up to the 200-MHz region. The ADA4937 can be used for frequencies up to 150 MHz; its main advantage is in dc-coupled applications with ADCs, because it can handle a wide range of common-mode output voltages.

Q. *What are important characteristics of the ADCs that I might use?*

A. The popular CMOS switched-capacitor ADC does not have an internal input buffer, so it has much lower power dissipation than buffered types. The external source connects directly to the ADC's internal switched-capacitor sample-and-hold (SHA) circuit (Figure 8). This presents two problems. First, the input impedance varies with time and as the mode is switched between *sample* and *hold*. Second, the charge injected into the sampling capacitors reflects back onto the signal source; this may cause settling delays for passive filters in the drive circuit.

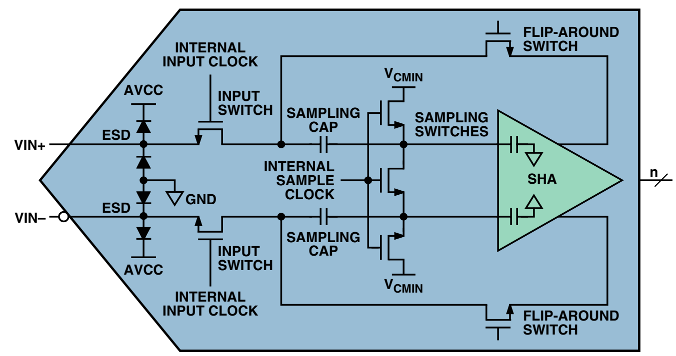

Figure 8. Block diagram of switched-capacitor ADC input stage.

It is important to match the external network to the ADC *track*-mode impedance, displayed in Figure 9. As you can see, the real (resistive) part of the input impedance (blue line) is very high (in the several kilohm range) at lower frequencies (baseband) and rolls off to less than 2 kΩ above 100 MHz.

The imaginary, or capacitive, part of the input impedance, the red line, starts out as a fairly high capacitive load and tapers off to about 3 pF (right-hand scale) at high frequencies.

To match to this input structure is a pretty challenging design problem, especially at frequencies greater than 100 MHz.

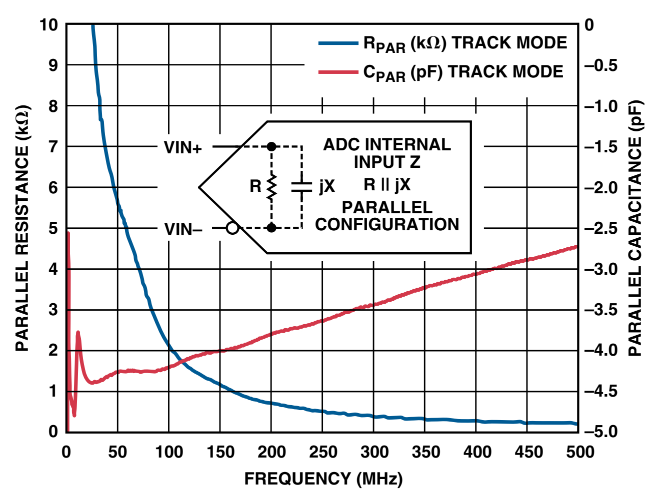

Figure 9. Typical input impedance graph of a switched-capacitor ADC in track mode.

The waveforms in Figures 10 and 11 illustrate the advantage of differential signaling. At first glance, the individual single-ended ADC input waveforms in Figure 10 look pretty bad. However, Figure 11 demonstrates that the corruption of the single-ended traces is almost purely a common-mode effect.

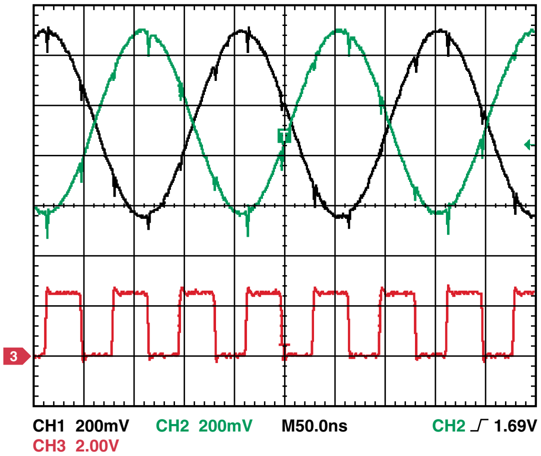

Figure 10. Single-ended measurement of a switched-capacitor ADC input relative to the clock edges.

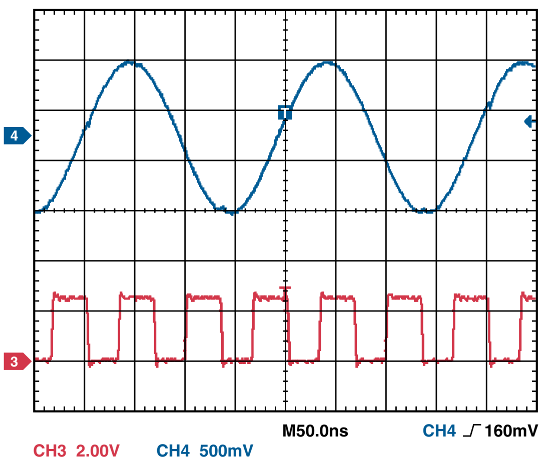

Figure 11. Differential measurement of a switched-capacitor ADC input relative to the clock edges.

Looking at the ADC inputs differentially (Figure 11), one can see that the input signal is much cleaner. The "corrupt" clock-related glitches are gone. The common-mode rejection inherent in differential signaling cancels out common-mode noise, whether from the supply, digital sources, or charge injection.

Buffered-input ADCs are easier to understand and use. The input source is terminated in a fixed impedance. This is buffered by a transistor stage that drives the conversion process at low impedance, so charge-injection spikes and switching transients are significantly reduced. Unlike switched-capacitor ADCs, the input termination has little variation over the ADC's analog input frequency range, so selection of the proper drive circuit is much easier. The buffer is specifically designed to be very linear and have low noise; its only downside is that its power consumption causes the ADC to dissipate more power overall.

Q. *Can you show me some examples of transformer and amplifier drive circuits?*

A. Figure 12 shows four examples of ADC input configurations using a transformer.

In baseband applications (a), the input impedance is much higher so the match is more straightforward than, and not as critical as, the match at higher frequencies. Usually, small-value series resistors will suffice to damp out the charge injection with a differentially connected capacitor. This simple filter attenuates the broadband noise, achieving optimal performance.

In order to get a well-matched input in broadband applications (b), try to make the input's real (resistive) component predominate. Minimize the capacitive terms with inductors or ferrite beads in shunt or series with the analog front end. This can yield good bandwidth, improve gain flatness, and provide better performance (SFDR) as seen using the AD92xx switched-capacitor ADC family.

For buffered high-IF applications (c), a double-balun configuration is shown, with a filter similar to the baseband configuration. This allows inputs of up to 300 MHz and provides good balancing to minimize even-order distortions.

For narrow-band (resonant) applications (d), the topology is similar to broadband. However, the match is in shunt instead of series, to narrow the bandwidth to the frequency specified.

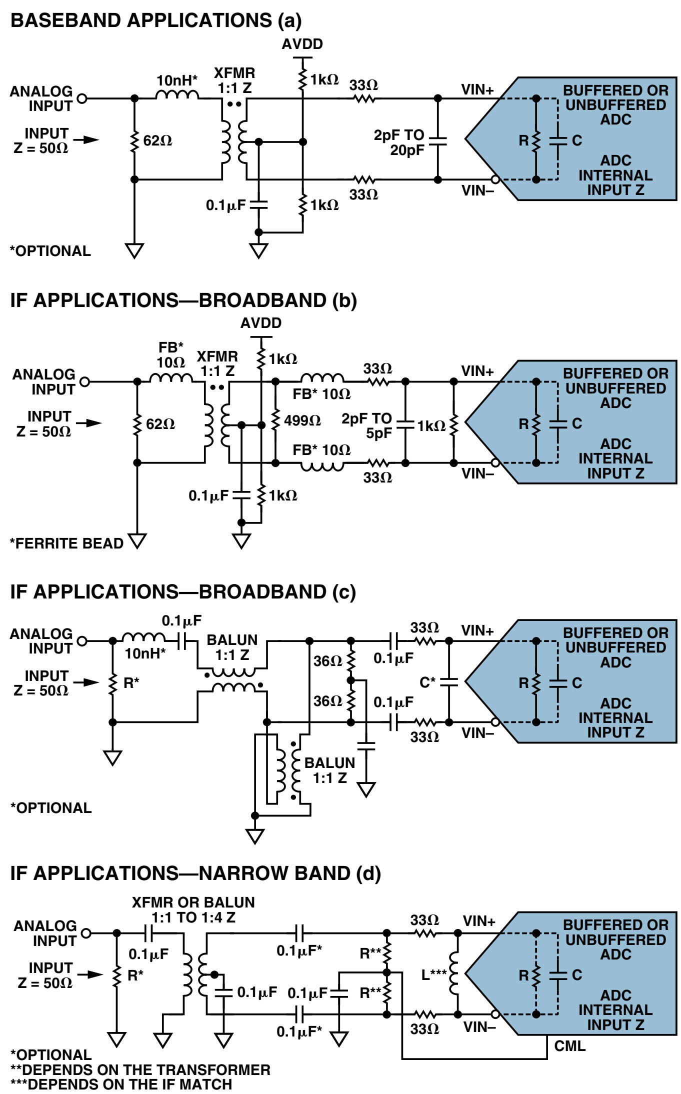

Figure 12. ADC front-end designs with transformer drive.

When using an *amplifier* with a buffered or unbuffered ADC in baseband applications, the design is fairly straightforward (Figure 13). Just make sure that the common-mode voltage of the amplifier is shared with the ADC, and use a simple low-pass filter to get rid of the unwanted broadband noise (a). For IF applications (b and c), the matching network is essentially similar to that in baseband, but usually has shallower roll-off. Inductors or ferrite beads can be used on the outputs of the amplifier to help extend the bandwidth if needed. This is not always necessary, however, because the amplifier's characteristics are less prone to changing over the band of interest than those of transformers. For narrow-band or resonant applications (d), the filter is matched to the output impedance of the amplifier to cancel the input capacitance of the ADC. Usually a multipole filter is used to get rid of broadband noise outside the frequency region of interest.

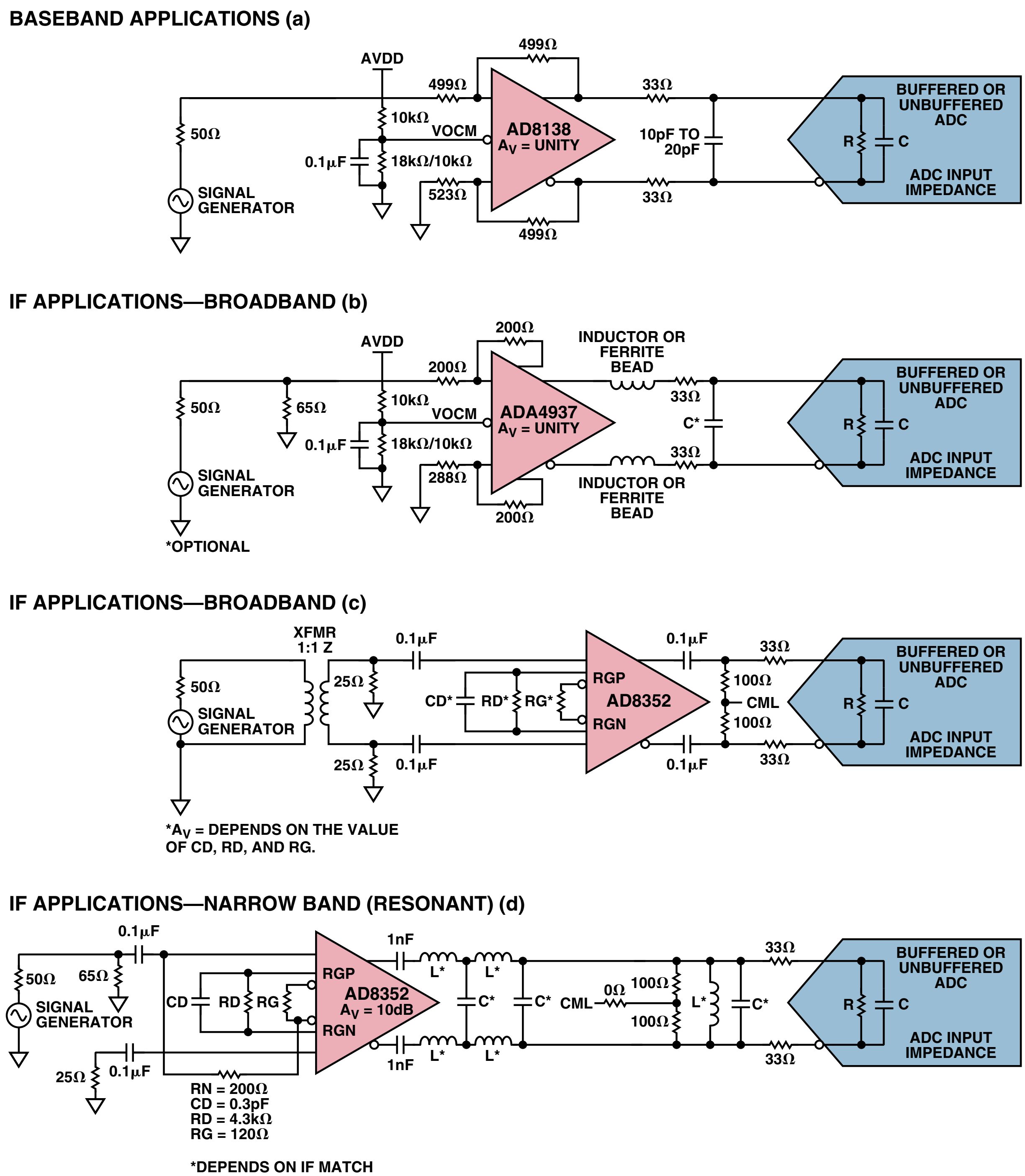

Figure 13. ADC front-end designs with amplifier drive.

Q. *Would you summarize the important points?*

A. When facing a new design, remember to:

- Understand the level of design difficulty.
- Rank the important parameters in your design.
- Include the ADC input impedance and the external components in the input circuit when determining the total load on the transformer or amplifier.

When choosing a transformer, always remember:

- Not all transformers are created equal.
- Understand transformer specifications.
- Ask the manufacturer for parameters that are not given, and/or do modeling.
- High-IF designs are sensitive to transformer phase imbalance.
- Two transformers or baluns may be needed for very high-IF designs to suppress the even-order distortions.

When choosing an amplifier, always remember:

- Note the noise specification.
- Understand amplifier specifications.
- For low-IF or baseband frequencies, use the AD8138/AD8139.
- For mid-IF, use the ADA4937.
- For high-IF designs, use the AD8352.
- Amplifiers are less sensitive to imbalance and automatically suppress even-order distortions.
- Some amplifiers can dc-couple to the ADC's input, e.g., the AD8138/AD8139 and ADA4937/ADA4938.
- Amplifiers inherently isolate the input source from output loading effects and can therefore be more useful than a transformer for dealing with sensitive input sources.
- Amplifiers can drive long distances and are especially useful when system partition dictates two or more boards in a design.
- Amplifiers may require another supply domain and will always add to system power requirements.

When choosing an ADC, always remember:

- Is the ADC internally buffered?
- Switched-capacitor ADCs have a time-varying input impedance and are more difficult to design with at high-IFs.
- If using an unbuffered ADC, always input-match in the *track* mode.
- Buffered ADCs are easier to design with, even at high IFs.
- Buffered ADCs tend to burn more power.

Finally:

- Baseband designs are the easiest with either ADC type.
- Use ferrite beads or low-Q inductors to tune out the input capacitance on switched-capacitor ADCs. This maximizes input bandwidth, creates a better input match, and maintains SFDR.
- Two transformers may be needed to deal with high IFs.

Q. *How about some references for further reading?*

A. Application Notes

AN-742, *Frequency-Domain Response of Switched-Capacitor ADCs.*

AN-827, *A Resonant Approach to Interfacing Amplifiers to Switched-Capacitor ADCs.*

B. Papers

Reeder, Rob. "Transformer-Coupled Front-End for Wideband A/D Converters." *Analog Dialogue* 39-2. 2005. pp. 3-6.

Reeder, Rob, Mark Looney, and Jim Hand. "Pushing the State of the Art with Multichannel A/D Converters." *Analog Dialogue* 39-2. 2005. pp. 7-10.

Kester, Walt. "Which ADC Architecture Is Right for Your Application?" *Analog Dialogue* 39-2. 2005. pp. 11-18.

Reeder, Rob and Ramya Ramachandran. "Wideband A/D Converter Front-End Design Considerations—When to Use a Double Transformer Configuration." *Analog Dialogue* 40-3. 2006. pp. 19-22.

C. Technical Data

AD9246, 80-/105-/125-MSPS 14-Bit, 1.8-V, Switched-Capacitor ADC

AD9445 105-/125-MSPS 14-Bit, 5-/3.3-V, Buffered ADC

AD9446 16-Bit, 80-/100-MSPS Buffered ADC

AD8138 Low-Distortion Differential ADC Driver

AD8139 Ultralow Noise Fully Differential ADC Driver

AD8350 1.0-GHz Differential Amplifier

AD8351 Low-Distortion Fully Differential RF/IF Amplifier

AD8352 2-GHz Ultralow Distortion Differential RF/IF Amplifier

ADA4937 Ultralow Distortion Differential ADC Driver

ADA4938 Ultralow Distortion Differential ADC Driver

ADC Switched-Capacitor Input Impedance Data (S-parameters) for AD9215, AD9226, AD9235, AD9236, AD9237, AD9244, AD9245. Go to their web pages, click on *Evaluation Boards*, upload Microsoft Excel spreadsheet.

REFERENCES—VALID AS OF FEBRUARY 2007

[1]ADI website: www.analog.com (Search) ADA4937 (Go)
[2]ADI website: www.analog.com (Search) AD9446-80 (Go)
[3]ADI website: www.analog.com (Search) AD8352 (Go)
[4]ADI website: www.analog.com (Search) AD9246-125 (Go)
[5]ADI website: www.analog.com (Search) AD9235-20 (Go)
[6]ADI website: www.analog.com (Search) AD8138 (Go)
[7]ADI website: www.analog.com (Search) AD8139 (Go)
[8]ADI website: www.analog.com (Search) AD8350 (Go)
[9]ADI website: www.analog.com (Search) AD8351 (Go)
[10]ADI website: www.analog.com (Search) AD8352 (Go)